Flavor tagging TeV jets for physics beyond the Standard Model

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Abstract. We present a new scheme for tagging boosted heavy flavor jets called “$\mu_x$ tagging.” At the LHC, the primary method to tag $b$-jets relies on tracking their charged constituents. However, when highly boosted, track-based $b$-tags lose efficiency, and the probability to mistag light jets rises dramatically. Using muons from $B$ hadron decay and defining a particular combination “$x$” of angular information and boost estimation, we find fairly flat efficiencies to tag $b$-jets, $c$-jets, light-quark jets, and light-heavy jets (containing $B$ hadrons from gluon splitting) of $\epsilon_b = 14\%$, $\epsilon_c = 6.5\%$, $\epsilon_{\text{light-light}} = 0.1\%$, and $\epsilon_{\text{light-heavy}} = 0.5\%$, respectively. We demonstrate the usefulness of this new scheme by showing the reach for discovery of a leptophobic $Z' \rightarrow b\bar{b}$ in the dijet channel.

1 Introduction

As searches for $W'$ and $Z'$ bosons at the CERN Large Hadron Collider (LHC) shift to TeV-scale energies, observation of their decay products becomes challenging. Observation of dijet resonances above QCD background is hampered by falling $b$-tagging efficiencies (28–15% around 1–2 TeV) and large light-jet fake rates of 1–2% [1]. In addition to the low purity ($\epsilon_{\text{fake}}/\epsilon_b \sim 1/10$), large uncertainties in the tagging efficiencies affect the mass limits; e.g., the ATLAS $b$-tag uncertainty is 35% for $p_T > 500$ GeV [2]. In order to discover multi-TeV physics beyond the Standard Model (BSM), we need a better $b$ tag with good efficiency and purity.

At this conference, we presented a new method for flavor tagging at TeV-scale energies called “$\mu_x$ boosted-bottom-jet tagging” [3]. This method is derived from kinematic first principles, and provides both a well-determined 14% efficiency for $b$-tagging, and a factor of 10 improvement in fake rejection over existing tags ($\epsilon_{\text{fake}}/\epsilon_b \sim 1/100$). In Sec. 2 we summarize the algorithm and cuts for the $\mu_x$ tag, show why it works, and plot its transverse momentum $p_T$- and pseudorapidity $\eta$-dependent efficiencies. In Sec. 3 we briefly describe the application of $\mu_x$ boosted-$b$ tagging to an analysis for discovery of a leptophobic $Z' \rightarrow b\bar{b}$. We summarize our results in Sec. 4.

2 $\mu_x$ boosted-$b$ tag

Consider a jet containing a semi-muonic decay of a $B$ hadron. In the center-of-momentum (CM) frame, the muon is emitted with a speed $\beta_{\mu,\text{cm}}$ and at an angle $\theta_{\text{cm}}$ with respect to the beam axis (see

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In the lab frame, the boost $\gamma_B$ of the $B$ hadron compresses its decay products into a narrow subjet at high energy. We define a lab frame observable

$$x \equiv \gamma_B \tan \theta_{\text{lab}} = \frac{\sin \theta_{\text{cm}}}{\kappa + \cos \theta_{\text{cm}}},$$

where $\kappa \equiv \beta_B/\beta_{\mu,\text{cm}}$.

While $\kappa$ is unobservable, for sufficiently boosted $B$ hadrons ($\gamma_B \gg \gamma_{\mu,\text{cm}} \geq 3$) the lab frame distribution of the muon count $N$ vs. $x$ is effectively independent of $\kappa$,

$$\frac{dN}{dx} \approx \frac{2x}{(x^2 + 1)^2}. \quad (2)$$

This leads to a universal shape in $x$ for highly boosted jets containing $B$ hadrons. Using this shape, we define the $\mu_x$ boosted-$b$ tag as a cut on two variables: We capture 90% of muons from $B$ decay by demanding $x < 3$. To further isolate $b$ decays, we note the hard fragmentation function for $b$ quarks leads to the $B$ hadron subjet carrying a large fraction $f_{\text{subjet}}$ of the total jet momentum. Hence, we demand

$$f_{\text{subjet}} \equiv \frac{p_{T\mu}}{p_{T\text{jet}}} \geq 0.5. \quad (3)$$

There are two challenges in applying the $\mu_x$ tag to real events: we must identify the correct decay remnant of the $B$ hadron to reconstruct its four-vector $p_{\text{subjet}}$, and we must deal with the missing muon neutrino. Most of the neutrino energy in the lab frame comes from the boost, so we use the measured four-vector of the muon as a proxy $p_\nu = p_\mu > 10$ GeV. In order to find the non-leptonic remnant “core” of the subjet, we need a more sophisticated algorithm.

In order to reconstruct the boosted subjet we first cluster the jet using the anti-$k_T$ algorithm with a $R = 0.4$. We then search for the core (generally the charm hadron remnant) by reclustering the muon and calorimeter towers with total jet energy fraction $f_{\text{tower}}^{\text{min}} > 0.05$ using a smaller $R_{\text{core}} = 0.04$. We assume $m_{\text{core}} = 2$ GeV (a typical charm hadron mass), and identify the “correct” core as the one which comes closest to $\sqrt{p_{T\text{subjet}}^2} = 5.3$ GeV. Since mismeasurements smear out the reconstructed energy of the subjet, if $m_{\text{subjet}} > 12$ GeV we constrain the subjet mass to be 12 GeV. The parameters of the $\mu_x$ tag are summarized in Table 1.

**Table 1.** A summary of parameters chosen for $\mu_x$ boosted bottom jet tagging.

<table>
<thead>
<tr>
<th>$R$</th>
<th>0.4</th>
<th>$m_{\text{core}}$</th>
<th>2 GeV</th>
<th>$p_{T\mu}^{\text{min}}$</th>
<th>10 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{core}}$</td>
<td>0.04</td>
<td>$m_B$</td>
<td>5.3 GeV</td>
<td>$x_{\text{max}}$</td>
<td>3 (x90%)</td>
</tr>
<tr>
<td>$f_{\text{tOWER}}^{\text{MIN}}$</td>
<td>0.05</td>
<td>$m_{\text{subjet}}^{\text{max}}$</td>
<td>12 GeV</td>
<td>$f_{\text{subjet}}^{\text{min}}$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

In spite of its non-trivial reconstruction, $x$ is effectively a dynamic angular cut on the muon. Defining $\xi$, the lab frame angle between the muon and the core, it is possible to calculate $\xi_{\text{max}}$, the
maximum $\mu$-to-core angle which produces $x \leq 3$. For “soft” muons ($E_\mu \ll E_{\text{core}}/18$), this angular cut is relatively tight

$$\xi_{\text{max}}^{\text{soft}} \approx 3 \frac{m_{\text{core}}}{E_{\text{core}}},$$

(4)

Once the muons become “hard” ($E_\mu \geq E_{\text{core}}/18$), the cut loosens significantly

$$\xi_{\text{max}}^{\text{hard}} \approx 3 \frac{m_{\text{subjet}}}{E_{\text{core}}},$$

(5)

While the transition between these limits depends explicitly on the muon’s $p_T$, this dependence is small until just below the hard threshold. Thus, not only is $x$ a smart angular cut — scaling with the energy of the core — it is a dual angular cut; tight for soft muons, looser for hard muons, and sensitive to the $p_T$ resolution of the muon system only within the narrow transition region.

The separation of reconstructed $b$ jets from light-quark-initiated jets can be seen in Fig. 2. Bottom jets ($b$-quarks hadronized as $B$ hadrons) above 500 GeV produce large $f_{\text{subjet}}$ and $x \sim 0.8$. Light jets (mostly $\pi$ and $K$) produce either incompatible values of $x > 3$, or random subjet recombinations that lead to small $f_{\text{subjet}}$. A small fraction of $b$ jets is not well-reconstructed (represented by the low-$f_{\text{subjet}}$ tail), but it has little effect on the total efficiency.

![Figure 2](image)

*Figure 2.* Density of reconstructed candidate tags with $\mu = 40$ pileup events as a function of $f_{\text{subjet}}$ vs. $x$ for (left) bottom and (right) light-quark-initiated jets.

We extract the standalone $\mu_x$ tagging efficiencies using PYTHIA 8.210 [4, 5] fed into an ATLAS-like version of DELPHES 3.2 [1], and a custom $\mu_x$ tagging module MuXboostedBTagging (available on GitHub [6]). In Fig. 3 we show separate efficiencies as a function of $p_T$ and $\eta$ for bottom jets, charm jets, light-light jets (where the muon came from a light-flavor hadron), and light-heavy jets (where a gluon split to $b\bar{b}/c\bar{c}$ — producing heavy-flavor hadrons in the final state). The kinematic nature of the tagging variables leads to fairly flat efficiencies in pseudorapidity, and when $p_T > 500$ GeV. The exception is the $\eta$ distribution for $B$ hadrons from gluon splitting. This leads to the intriguing possibility that the $g \to b\bar{b}$ contribution to jets in the Monte Carlo could be calibrated using the rapidity dependence of these highly-boosted jets.

### 3 A search for leptophobic $Z' \to b\bar{b}$

Very massive $Z'$ bosons are expected to exist in many BSM models. We test the $\mu_x$ boosted-bottom tag by examining the reach at a 13 TeV LHC for a leptophobic $Z'$ decaying to $b\bar{b}$ or $c\bar{c}$. For this study
we choose a $U(1)'_B$ Lagrange density

$$\mathcal{L} = \frac{g_B}{6} Z_B' \bar{q} \gamma^\mu q,$$

(6)

with a flavor-independent coupling to quarks [7, 8].

We simulate the signal and backgrounds using a MLM-matched MadEvent sample [9] and CT14lo PDFs [10] fed through PYTHIA into DELPHES. In addition to demanding one or two $\mu_x$ tags (as defined in Sec. 2), we require $|\eta_{jj}| < 2.7$, and $\Delta \eta_{jj} < 1.5$. We reconstruct a dijet mass out of the two leading-$p_T$ jets, and look for a resonance in the mass window $[0.85, 1.25] \times M_{Z'}$.

The results for 5$\sigma$ discovery of this leptophobic $Z'$ are shown in Fig. 4 for a two-tag, and one-tag inclusive sample, compared to current exclusion limits from Ref. [7]. In 100 fb$^{-1}$ of integrated luminosity at 13 TeV, a two $b$-tag analysis could discover a $Z'$ of 3 TeV if the universal coupling $g_B \sim 2.5$. For this particular model, the single-tag inclusive search would be more effective — allowing for discovery up to nearly 1 TeV above current mass limits. Should a discovery not be made, the two-tag search (not shown) would set a 95% C.L. exclusion comparable to the one-tag discovery reach; while the one-tag search would set a 95% C.L. exclusion that can access $g_B$ couplings a factor of 2 smaller than current limits, and masses up to 2 TeV higher.

4 Conclusions

In this paper we discuss the new $\mu_x$ boosted-bottom-jet tag. Combining angular information $x$ from $B$ hadron decay with jet substructure $f_{\text{subjet}}$ in TeV-scale jets allows for tagging efficiencies of $\epsilon_b = 14\%$, $\epsilon_c = 6.5\%$, $\epsilon_{\text{light-light}} = 0.1\%$, and $\epsilon_{\text{light-heavy}} = 0.5\%$, respectively. The results here focused on ATLAS because their standalone non-isolated muon tagging efficiency is publicly available. We expect that if CMS has similar non-isolated muon tagging capability this tag will be just as effective, since it is kinematically driven and not sensitive to fine details of the detector.

When applying the $\mu_x$ tag to a search for leptophobic $Z'$ bosons, we find that the reach for discovery at a 13 TeV LHC is about 1 TeV higher than current limits. If a $Z'$ is not found, 95% C.L.

Figure 3. $\mu_x$ tagging efficiency vs. (left) jet $p_T$ and (right) $\eta_{\text{jet}}$. Solid (dashed) lines include $\mu = 0$ ($40$) pileup events.
Figure 4. $5\sigma$ discovery reach for a leptophobic $Z'$ with universal coupling in the with one or two boosted-$b$ tags at a 13 TeV LHC compared to exclusion limits from Ref. [7]. Also shown is the 95% C.L. exclusion reach of the one-tag analysis.

exclusion limits can be set up to 2 TeV higher, or for $g_B$ couplings a factor of 2 smaller, than the current limits. In addition to $Z' \to b\bar{b}$, the $\mu_x$ tag should be of immediate use in the search for $W' \to t\bar{b}$ in the boosted-top and boosted-bottom channel [11] conducted by the ATLAS Collaboration [2].

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References